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Effect of substrate on the radiation efficiency of different microstrip phased array antennas

Birendra Singh
Department of Physics, Institute of Basic Sciences, Agra University,
Khandari Campus, Agra-282 002, India

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Abstract : In the present work, we perform an analysis to study the surface wave (SW) losses of three different microstrip phased array antennas immersed in ionized (plasma) medium. The calculations have also been made for the radiation efficiency of two element array presented by Saxena *et al* (1989). The SW losses are calculated using the data on the substrate permittivity, its thickness and free space wavelength. It is found that the surface wave losses together with plasma wave (electroacoustic) losses affect the radiation efficiency of microstrip array antennas adversely. The inclusion of SW losses changes the radiation efficiency more significantly for the plasma frequencies $\omega_p < 0.5\ \omega_0$ (ω_0 is the source frequency)

Keywords : Surface wave, microstrip array antennas, radiation efficiency

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1. Introduction

Microstrip patch antennas and their arrays have been the centre of attention in the past decades due to their exclusive merits such as light weight, flat profile, low manufacturing cost and compatibility with integrated circuits [1–3]. These antennas are becoming increasingly popular in many communication systems for aerospace vehicles, satellites and other systems [4–6]. Antennas mounted on such aerospace vehicles encounter plasma medium during their travel in space, as a result of which radiation properties are altered significantly. This change is caused due to the generation of electroacoustic (plasma) waves in addition to electromagnetic waves [7–9]. Radiation properties are also affected by the occurrence of the surface waves produced by the grounded substrate [10,11]. The power carried by surface waves is considered as a loss because it is trapped in the dielectric substrate. Earlier studies of microstrip antenna arrays in plasma medium [8,9,12] did not consider the effects of surface wave excitation. The substrate thickness, losses in the feed structure and fabrication tolerences are important factors in the excitation of higher order SW-modes. The lowest order SW mode is excited due to the presence of the air dielectric boundary in the structure. Bhattacharyya and Garg [11] have calculated the wall addimittance of a circular patch antenna taking into account SW excitation due to TM_n modes by using a magnetic current in the Hankel transform domain. However, their analysis is useful only for moderately thin substrates having narrow band-width performance Nauwelaers and Van De Capelle [13] have presented a closed wave expression for the radiation efficiency of rectangular patch antennas. In the present study we have generalised the method due to Nauwelaers and Van De Capelle for array antennas. Our motivation is to study the effect of SW losses on the radiation efficiency of 4 element : (a) linear array antenna, (b) planar array antenna and (c) Circular array antenna in plasma medium. The method of analysis is presented in section II and results are discussed in section III.

2. Method of analysis

The configurations of three types of array antennas are shown in Figure 1.

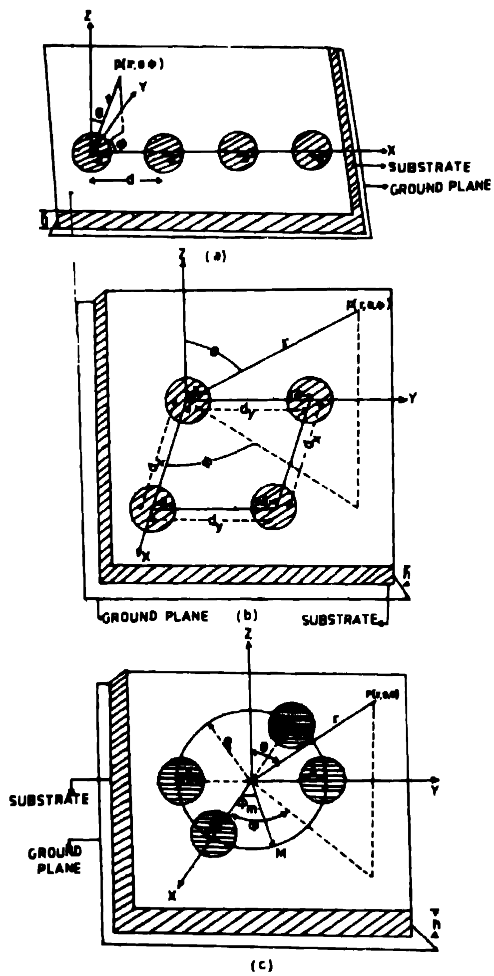

Figure 1. Configuration of different four element circular patch microstrip phased arrays. (a) linear array, (b) planar array and (c) circular array.

We have developed expressions for the far-zone EM mode and the P-mode components of radiation fields for linear, planar and circular array antennas available in the literature [8, 9, 14]. The radiated power into the far field is determined by integrating

Table 1. Calculated values of radiation effieincies (η and η_{eff}) for microstrip linear, planar and circular array antennas with different ratios of plasma to-source frequency (ω_p/ω_0).

SN	$\frac{\omega_p}{\omega_o}$	$A = \sqrt{1-\frac{\omega_p^2}{\omega_o^2}}$	4-element Linear array		2 × 2-element planar array		4-element circular array		2-element array	
			η (L)% eq. (3)	η_{eff} (L)%	η (P)% eq. (3)	η_{eff} (P)%	η (C)% eq. (3)	η_{eff} (C)%	η (S)% eq. (3)	η_{eff} (S)%
1	0	1.0	100	100	100	100	100	100	100	100
2.	0.1	0.994	72.9	57.4	95 1	70.3	97.8	71.7	89.1	66.9
3	0.2	0.979	65.1	52.4	90.1	67.5	96.4	70.9	81.8	62.7
4.	0.3	0.953	58.9	48.4	77.7	60.2	93.5	69.3	72.7	57.3
5	0.4	0.916	54.0	44.9	66.2	53.2	89.7	67.3	56.4	46.7
6	0.5	0.866	50.5	42.6	60.9	49.7	84.6	64.4	34.5	30.6
7	0.6	0.8	38.2	33.5	56.2	46.5	78.4	60.7	13 6	12.9
8.	0.7	0.714	27.5	24.9	48.3	40 9	72.6	57.2	4.5	4.5
9	0.8	0.6	10.7	10.5	40.0	34.8	65.9	52.9	1.8	1 8
10	0 9	0.435	3.3	3.2	20.1	18.7	57.5	47.4	0	0
11	0 99	0.141	1.2	1.2	2.2	2 2	2 0	1.9	–	–
12.	1.0	0	0	0	0	0	0	0	–	–

the Poynting vector over a large sphere. Nauwelaers and Van De Capelle [13] have expressed the radiation efficiency (η_1) in terms of space wave power (P_e) and surface wave power (P_s) as

$$\eta_1 = \frac{P_e}{P_e + P_s} = \left(1+\frac{P_s}{P_e}\right)^{-1}, \tag{1}$$

where $$\eta_1 = 1-3.4H + \frac{1600}{\varepsilon_r^3}\left(H^3 - 100H^{5.6}\right) \tag{2}$$

with $$H = \sqrt{(\varepsilon_r - 1)}\left(\frac{h}{\lambda_o}\right).$$

Here, ε_r and h are the relative permittivity and thickness of dielectric substrate in the antennas. Singh and Pourush [8,9] and Singh [14] have considered electromagnetic mode power (p_e) and electroacoustic mode power (p_p) and defined radiation efficiency η as

$$\eta = \left(1 + \frac{P_p}{P_e}\right)^{-1}. \tag{3}$$

Considering (1) and (3), the effective value of radiation efficiency (η_{eff}) is thus obtained as

$$\eta_{eff} = \frac{\text{Useful power}}{\text{Total radiated power}} = \frac{P_e}{P_e + P_p + P_s}. \tag{4}$$

In other words,

$$\eta_{eff} = \left(\frac{1}{\eta} + \frac{P_s}{P_e}\right)^{-1}. \tag{5}$$

The values of η_{eff} have been computed for the 4-element linear array antenna [η_{eff} (L)], 2 × 2 element planar array antenna [η_{eff} (P)] and 4-element circular array antenna [η_{eff} (C)]

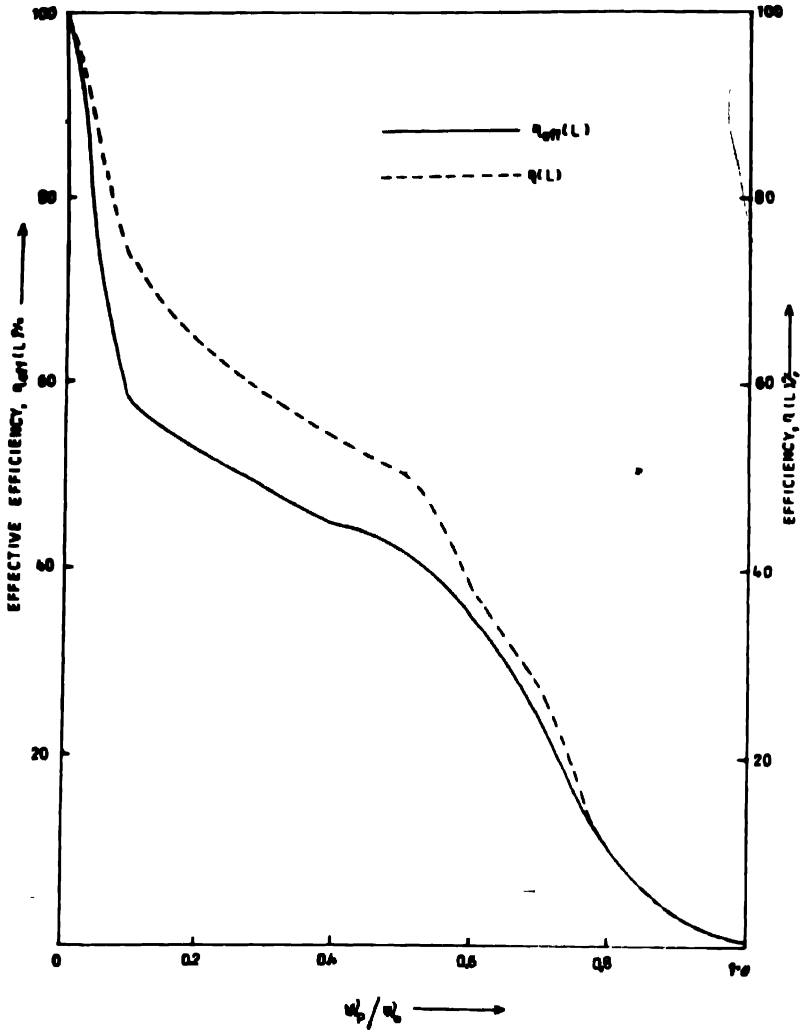

Figure 2. Variation of η_{eff} and η with plasma-to-source frequency (ω_p/ω_0) for 4-element linear array antenna.

for the case of substrate permittivity $\varepsilon_r = 3.55$, substrate thickness $h = 0.16$ cm and free space wave length $\lambda_o = 3$ cm. These particular values of ε_r, h and λ_o have been used by earlier workers [8,9,15] for studying the radiation efficiency of array antennas in plasma medium. We have therefore, used the same values for calculating SW losses in order to make a meaningful comparison. The radiation efficiency for the two element array [η_{eff} (S)] discussed by Saxena *et al* [15], has also been estimated and modified under the same input conditions. The computed values of radiation efficiency for these four cases are presented in Table 1.

3. Results and discussion

In the present study, we have estimated surface wave losses which are found to deteriorate the performance of array antennas appreciably. Figures 2, 3 and 4 illustrate the variation of

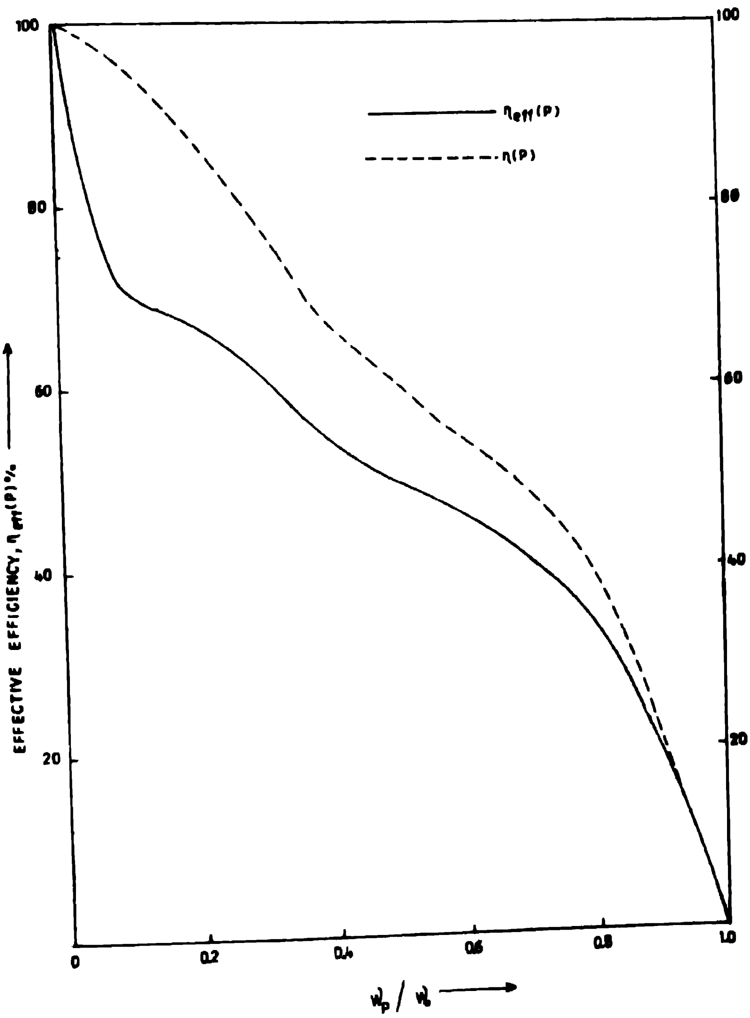

Figure 3. Variation of η_{eff} and η with plasma-to-source frequency (ω_p/ω_o) for 2 × 2 element planar array antenna.

radiation efficiency of microstrip linear, planar and circular array antennas respectively with different ratios of plasma-to-source frequency (ω_p/ω_o).

In all three cases, the effective radiation efficiency (η_{eff}) which combines both the surface wave losses and plasma wave losses, falls drastically to 55-70% from the peak value (100%), at around $\omega_p/\omega_o \approx 0.1$. The fall is maximum in case of linear array and minimum in the case of circular array. This can further be considered as a strong point in favour of circular array configuration [14]. In Figure 5 we have considered the case of two element array [15]. In this plot, we observe the same abrupt fall of radiation efficiency at $\omega_p/\omega_o \approx 0.1$. Beyond this value it decreases slowly and finally at around $\omega_p/\omega_o \approx 0.6$, it merges with the original trend of radiation efficiency in plasma medium. The inclusion

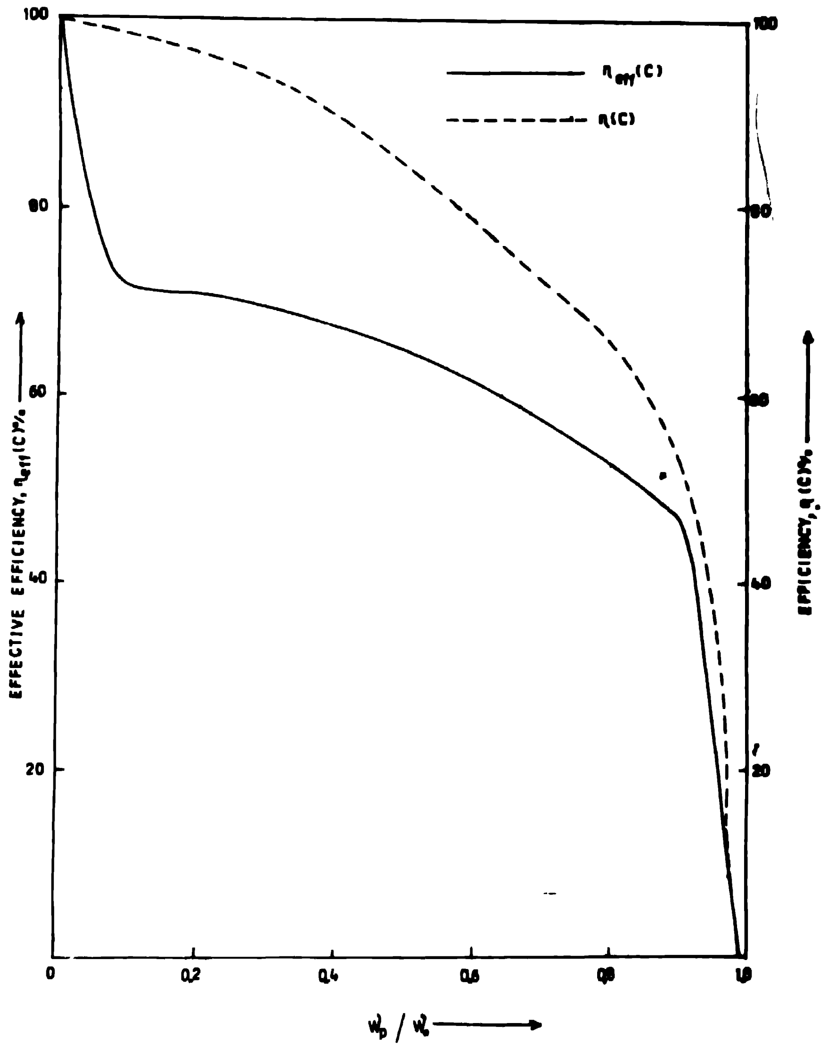

Figure 4. Variation of η_{eff} and η with plasma-to-source frequency (ω_p/ω_o) for 4-element circular array antenna.

of SW losses changes the radiation efficiency for the plasma frequencies $\omega_p < 0.5\,\omega_o$. At higher values of ω_p/ω_o, the change in radiation efficiency is much less. An interpretation for this prediction can be given on the basis of eq. (5) which takes into account the plasma as well as SW losses. In the high plasma frequency region, the calculated values of P_s/P_e are quite small as compared to $1/\eta$. Values of the radiation efficiency (η_{eff}) calculated from eq. (5) are nearly equal to the corresponding values of radiation efficiency calculated from eq. (3) which does not take account of the SW losses.

To conclude, the present study is supposed to be useful particularly for space vehicles because such type of array antennas (linear and planar) can be mounted on the flat surface as well as on the curved surface (circular) of the vehicle.

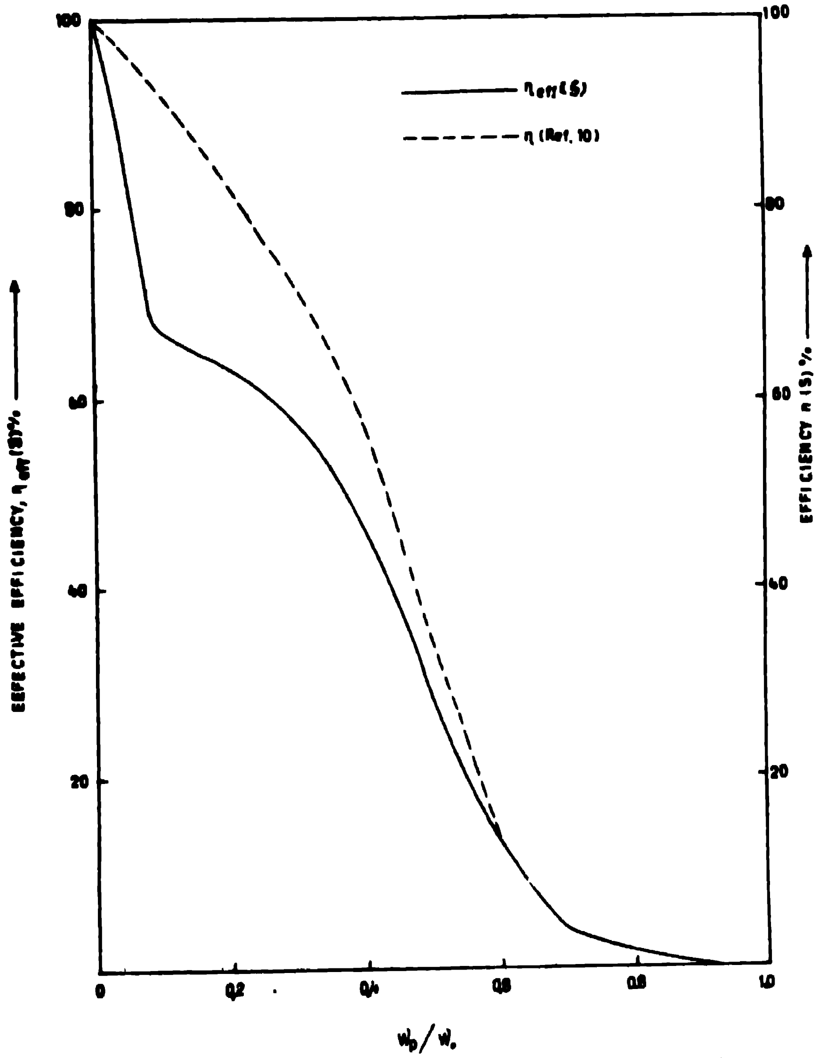

Figure 5. Variation of η_{eff} and η with plasma-to-source frequency (ω_p/ω_o) for 2-element array antenna.

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